Economic Growth and CO_2 Emissions with Endogenous Emission Regulations: A Computable General Equilibrium Analysis*

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Abstract

It is widely known that emissions of greenhouse gases from anthropogenic activities have been dramatically increasing at the unprecedented rate over the past several decades, and causing the global climate change. To assess the future trends of such global climate change, it is necessary to project future greenhouse gas emissions. In this paper, we explore the effects of further economic growth on CO_2 emissions with the use of a multi-sector, multi-region global CGE model, and with explicit consideration to the endogeneity of emission regulations, i.e. the dependence of regulations on the level of income. The relationship between income level and emission regulations are derived from the consequence of the Kyoto Protocol type emission regulations. Our main finding is summarized as follows. Carbon taxes rise in all regions with economic growth because all regions, especially LDC regions, enjoy the rise in per capita income. However, the responsiveness of carbon taxes to income change is too weak to restrain the increase in emissions. In other words, given the degree of the responsiveness of regulations inferred from the acceptance of the Kyoto Protocol type regulations, carbon emissions are likely to increase all over the world along with further economic growth.

Keywords: The environmental Kuznets curve; CO_2 emissions; carbon tax; endogenous regulation; economic growth.

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1 Introduction.

It is widely known that emissions of greenhouse gases from anthropogenic activities have been dramatically increasing at the unprecedented rate over the past several decades, causing the rapid increase in atmospheric greenhouse gas concentration, and it has begun to affect the global climate (IPCC, 2001b). The many evidences that these climate changes have exercised adverse effects on physical, biological and human systems have already been reported (see IPCC, 2001a). Moreover, there is a widespread concern that the continuing global climate change is likely to have significant influence on the global environment in an irreversible and dangerous way.

To assess the future trends of global climate change, it is necessary to project future greenhouse gas emissions. The projection of future greenhouse gas emissions are conducted by many institutions and researchers (e.g. IPCC, 2000; DOE, 2001). Most of these researches project that the global greenhouse gas emissions will continue to rise with world economic growth in the absence of mitigation policies. However, it is often pointed out that some types of emissions have not necessarily increased along the process of economic growth, and there are several empirical evidences that emissions and economic growth have the following relationship: emissions increased with income growth at the low level of per capita income, but they began to decrease over some levels of per capita income, and continued to decrease afterward. This relationship between emissions and per capita income is known as '*the inverted-U relationship*' or '*the environmental Kuznets curve*'. The following empirical studies derive the inverted-U relationship between emissions and per capita income: Grossman and Krueger (1993, 1995), Selden and Song (1994), Gale and Mendez (1998), and Antweiler, Copeland and Taylor (2001). Most of these studies investigated the relationship between air or water pollutants and economic growth (or increase in income).

To explain the existence of the inverted-U relationship, the two effects called *scale* and *technique* effects are usually used (e.g. Grossman and Krueger, 1993; Antweiler et al., 2001). The argument goes as follows. On the one hand, economic growth usually brings about expansion of production and consumption activities, which tends to result in increase in emissions. This effect is called the scale effect. On the other hand, economic growth brings about increase in per capita income. The increase in per capita income raises people's concerns on environmental quality, and this in turn changes into the more stringent environmental regulations through political process. Therefore emissions tend to decrease as a result of increase in per capita income. This latter effect is called the technique effect because the more stringent regulations usually means the adoptions of cleaner technology in general. The observed inverted-U relationship is explained in terms of these two offsetting effects as follows: at low per capita income, the scale effect dominates the technique effect, and thus, emissions increase with increase in per capita income. However, as per capita income increases, the technique effect becomes stronger, and outperforms the scale effects over some turning point, resulting in the decrease in emissions with the further increase in per capita income.

To sum up, we can say that the arguments of the environmental Kuznets curve view the economic growth with consideration to the endogenous nature of environmental regulations. This endogeneity (or dependence on income) of environmental regulations can be a crucial point in designing the policies for environment protection because it means that a policy which improves environmental quality in the short run may be bad in the long run. In other words, it may be that the desirable policy is not to restrain economic growth but to let an economy grow as fast as possible and then introduce environmental regulations after people's concern for environmental quality sufficiently increases. Since climate change generates inter-generational and international externalities and there is no supranational authority who can force all countries to correct externalities, whether climate change mitigation policy is implemented or not crucially depends on *voluntary* actions of governments in the present generation. In this sense, the environmental Kuznets curve argument matters especially for climate change problem.

From the same point of view, Holtz-Eakin and Selden (1995) investigated the relationship between CO_2 emissions and per capita income. Their approaches and results are summarized as follows. They estimated the reduced form equation in which per capita carbon emission is entered as an explained variable and income per capita as an explanatory variable, using the panel data of 130 countries and 1951-1985 periods[1]. Furthermore, they conducted the projection of future CO_2 emissions with the estimated parameters. Their findings are (i) there is the inverted-U relationship between per capita income and per capita CO_2 emissions, (ii) however, the turning point per capita income ($35428 per capita income, 1985 US. dollar) is significantly large and lies out of their sample (the largest income in the sample is US's $15000) (iii) The global CO_2 emissions are likely to continue to rise in the near decades because the per capita incomes of most growing countries remains below the turning point income and, at the same time, the population in these regions will continue to rise.

Their approach is the standard one commonly employed in the studies on the inverted-U relations, but has the following shortcomings. First, the equation they estimated is the reduced form and is not based on the sound theoretical structure. Although you may be able to interpret the relationship between per capita CO_2 emissions and per capita income in terms of two effects mention above, it is unclear whether such interpretation itself is appropriate or not from their analysis. Moreover, you can not get from their analysis the details of what economic growth brings about to economies. For example, if emissions increase in a region with economic growth, there are a lot of possible reason for this: change in technologies, change in energy compositions, change in patterns of production and consumption, and so on. You cannot derive any answer to such question from their analysis.

The second problem lies in the data used in their analysis. As pointed out above, the inverted-U relationship is usually interpreted by the scale and technique effects and

[1] The estimated equation is

$$c_{it} = \beta_0 + \beta_1 y_{it} + \beta_2 y_{it}^2 + \gamma_t + f_i + \varepsilon_{it} \tag{1}$$

where *i* and *t* are time and country index respectively, c_{it} is per capita CO_2 emission, y_{it} is per capita income, and γ_t, f_i, and all βs and are estimated parameters.

it is reasonable to think that the technique effect is brought about as a result of the more stringent emission regulations because it is not plausible for citizens or firms voluntarily to adopt more cleaner technology or to decrease the use or consumption of polluting goods. However it is clear that there has been no regulation on CO_2 emissions adopted in any countries in the period of their datasets: 1951-1985. This means that, from the beginning, there is no positive reason for us to expect the inverted-U relationship from the past observations.[2] Nevertheless, they derived the inverted-U relationship and provided no reason for it. Moreover, they conducted the future projection, using the parameters estimated using such dataset. It follows that their projection does not include any policy effects (technique effects) because there is no policy adopted in the the dataset used for parameter estimation.

In this paper, we also investigate the relationship between carbon emissions and economic growth. Our approach has the following characteristics. First, we employ the multi-sector, multi-region computable general equilibrium (CGE) models which are widely used in analyses of CO_2 emission mitigation policy, e.g., Jorgenson and Wilcoxen (1993), Bernstein, Montgomery and Rutherford (1999), McKibbin, Ross, Shackleton and Wilcoxen (1999), Paltsev (2000a,b), Böhringer (2000), and Babiker and Rutherford (2001). The multi-sector, multi-region CGE model has the following advantages: we can explore the details of the changes accompanied with economic growth, for example, changes in energy compositions, energy intensity and so on. Moreover, we can make clear the effects of regulations on emissions. This advantages is noteworthy as compared to econometric method that estimates a reduced form equation because the latter approach is not suitable for policy analysis.

The second feature of this paper is that we explicitly consider the dependence of CO_2 regulations on income levels. In the previous studies on the environmental Kuznets curve including Holtz-Eakin and Selden (1995), the regulations on emissions have not been considered explicitly (moreover, it is often the case that they do not distinguish the scale and technique effects) although they use the technique effect (regulations) in interpreting estimated results. On the contrary, we give explicit consideration to the dependence of regulations on income levels, and incorporate it into the model. Taking this approach enables us to evaluate the details of the consequences of economic growth in terms of not only the direct scale effects, but also the indirect technique effects and also can evaluate the strength of both effects separately.

Since emissions regulations like the one embodied in Kyoto Protocol are likely to be adopted in the near future (UNFCCC, 1997), and since a lot of studies investigating the effects of economic growth in the absence of mitigating policies have already been done, it seems important to explore the effects of economic growth on emissions giving consideration to endogenous nature of emission regulations. As far as the authors' knowledge, there is no empirical studies which take account of explicitly the endogeneity of

[2]However, there are several possible factors that economic growth lead to decrease in carbon emissions in spite of the absence of regulation on them. First, energy composition may alter with economic growth so that carbon intensive energy is replaced with less carbon intensive energy (e.g. from coal to nuclear). Second, introduction of other regulations such as air pollution regulation could have side effects that reduce carbon emissions.

CO_2 emission regulation or the dependence of CO_2 regulation on income level, and this is the first attempt to try to consider such a effect.

The key of our analysis is the way to incorporate the endogeneity of emission regulations into the model, in other words, how to make the regulations depend on income levels. As already pointed out, no regulations (except for slight carbon taxes adopted in several European countries since 90's) have been adopted in the past. Therefore, we cannot derive any meaningful relationship from the past data and we need take another approach. The approach we employ is to make use of the fact that the Kyoto Protocol type emission regulations are likely to be adopted in the near future. We presume that the Kyoto Protocol type emission regulations is imposed on economies at 2010, then derive the income-regulations relationship from the consequences of the such policy interventions.

The main issue of our analysis is to make clear the impacts of economic growth on carbon emissions with emission regulations determined endogenously, especially, to answer the question whether economic growth increase carbon emissions or not. As a result of numerical analyses, we get the following results. Although economic growth raises per capita income and, therefore, emission regulations are reinforced substantially in all regions, emissions increase significantly in all regions. It is because the responsiveness of regulations against income change, which is inferred from the Kyoto Protocol type regulations, is too weak to restrain emissions, in other words, the technique effects are much smaller than the scale effects. We tested this finding by doing some sensitivity analyses and found that the above results remain unchanged. Although the Environmental Kuznets curve argument suggests that economic growth does not necessarily harm environment, our result shows that the argument is likely not to be applicable to CO_2 emissions.

The remainder of the paper is organized in the following way. Section 2 describes the model. Section 3 describes the datasets, parameter calibration, and the way to derive the income-regulations relationship. Section 4 presents the numerical results of the simulation and its interpretation. In Section 5, the concluding remarks are provided.

2 The Model.

The model in this paper is based on the GTAP-EG (see Rutherford and Paltsev, 2000a) and almost the same as the ones employed in Paltsev (2000a,b), Böhringer (2000), and Babiker and Rutherford (2001). The detailed description of the model is found in Rutherford and Paltsev (2000a).

The model is a multi-sector, multi-region, static general equilibrium one. The world is divided into twelve regions, and each economy is composed of eight production sectors. The lists of regions and sectors in the model are provided in the tables of Appendix A. The choice of regions is made so that it is compatible with the regions employed in DOE (2001) datasets. There are six Annex I regions and six non-Annex I regions. The sectors in the model have been chosen to highlight the following two aspects: (i) the difference in carbon intensities among different energies, and (ii) the difference in energy intensities among non-energy sectors. As to (i), the energy sectors are disaggregated into five different sectors: crude oil (CRU), coal (COL), gas (GAS), refined oil (OIL), and electricity (ELE).

By distinguishing energy sectors in this way, we can see the difference in carbon intensities among different energy. Moreover, to take account of (ii), non-energy sectors are divided into three different sectors: an energy-intensive sector (EIS), a non energy-intensive sector (Y), and a saving good sector (CGD). All markets in the model are perfectly competitive and all equilibrium prices are determined so as to clear all markets.

We divide production sectors into two broad categories: fossil fuel production sectors (crude oil, coal, gas) and non-fossil fuel production sectors (all other sectors). We assume that all production functions in all sectors have the nested CES form, but that fossil fuel sectors and non-fossil fuel sectors have the different structures. There are three primary production factors, labor, capital, and fossil fuel resources. Fossil fuel resources are used only in fossil fuel production sectors. All factors are assumed to be internationally immobile, and moreover fossil fuel resources are assumed to be sector-specific in fossil fuel sectors.

The demand side of each region is derived from optimizing behavior of a representative agent. His utility consists of saving good and final goods consumption, and he makes the decision so as to maximize his utility under the budge constraint. His income is the sum of factor income, taxes revenue, and exogenous capital inflows.

All regions in this model are connected with each other through international trade in goods and trade in goods is characterized by trade flows of pairs of countries. We assumes that goods produced in different regions are regarded qualitatively distinct (Armington, 1969). Moreover we assume that, to ship goods internationally, it is necessary to input the transportation services. As to the policy instruments appeared in this model, there are various types of taxes and subsidies including consumption taxes, intermediate input taxes, output taxes, and factor taxes. All tax revenues are assumed to be transfered to the representative agent in a lump-sum way. In our static model, the sources of economic growth are given by exogenous increase in factor endowments and technology improvements.

In the following subsections, we present the more detailed description of individual components of the model (production structures, demand structure, and so on). See also the algebraic representation of the model in Appendix C.

2.1 Production Structure.

There are five energy production sectors, crude oil (CRU), coal (COL), gas (GAS), refined oil (OIL), and electricity (ELE). Crude oil is produced domestically or imported, and it is used to produce refined oil which are used as an input to production and final demand. Electricity is not traded and is produced using coal, oil, gas, and non-fossil intermediates. Final energy products (refined oil, gas, and coal) are supplied as inputs both to production and to final demand.

All production sectors have a nested CES type production structure, reflecting the difference of substitutability between various inputs. We also assume that goods produced for the domestic market and goods produced for the export market are differentiated, and that they are subject to a constant elasticity of transformation (CET).

As has been pointed out above, we divide the production sectors into two categories, fossil-fuel and non-fossil-fuel production sectors and assume that these two have the different production structures. Let us explain them in turn.

2.1.1 Fossil Fuel Sectors.

Fossil fuel production activities include extraction of crude oil, natural gas, and coal. Its production structure is presented in Fig. 3 of Appendix where a value to the right of the arc represents an elasticity of substitution. Fossil fuel output is produced as an aggregate of a resource input and a non-resource input composite. The non-resource input for the production is a fixed coefficient (Leontief) composite of labor and the Armington aggregation of domestic and imported intermediate inputs. The elasticity of substitution between non-resource intermediates and labor is equal to zero.

The elasticity of substitution between fossil resource input and non-resource inputs composite is calibrated from an exogenously given price elasticity of fossil fuel supply. We assume that the benchmark value of supply elasticity is unity. The degree of elasticity of transformation between the domestic supply and export supply in gas is assumed four, but crude oil and coal sectors are assumed to have CET elasticities of infinity (i.e. perfect substitution) because there is empirical evidence that the markets for these two goods are highly integrated internationally.

2.1.2 Non-Fossil Fuel Sectors.

Non-fossil fuel production (including electricity and refined oil) has a different structure from the one in fossil fuel sectors. Fig. 2 in Appendix illustrates the nesting and typical elasticities employed in non-fossil production sectors. Non-Fossil fuel Output is produced with fixed coefficient (Leontief) aggregation of non-energy intermediates and an energy primary factor composite. The energy composite and primary factor composite are aggregated through a CES function with elasticity 0.5. Primary factor composite is a Cobb-Douglas aggregation of labor and capital stock. The energy composite is a CES aggregation of electricity and non-electric energy input composite with elasticity of substitution of 0.5. Then non-electric energy composite is a CES aggregation of coal and liquidity energy composite. The liquidity energy composite is also a CES aggregation of gas and refined oil. We assume that non-fossil fuels sectors have constant elasticity of transformation of four.

2.2 Other Sectors.

To explain the bilateral cross-hauling in goods trade, we use the so-called Armington assumption: goods produced in different regions are qualitatively distinct (see Armington, 1969). To incorporate the Armington aggregation into the model, we presume an artificial sector which aggregates the domestic good and import composite. We call this sector *the Armington aggregation sector* and assume that the elasticity of substitution between the domestic good and import composite is four. Produced Armington composite is used for both final consumption and intermediate input to production.

We also presume *the import aggregation sector* which aggregates imports from different regions into a composite import good. The elasticity of substitution between goods from different regions is assumed to be eight. International trade in goods require transportation services which are provided by *the world transport sector*.

In contrast to other goods, crude oil and coal are assumed to have a sufficiently large elasticity of substitution both in the Armington aggregation sector and import aggregation sector, reflecting the empirical evidence that markets for these two goods are highly integrated internationally.[3] The nesting structure of the Armington aggregation and import aggregation sectors is presented by Fig. 4.

Finally, the structure of the transport service sector is presented in Fig. 6. The international transport services are assumed to be a Cobb-Douglas composite of goods provided in the export markets in each region.

2.3 Final Demand Structure.

The representative agent's utility has the structure depicted in Fig. 5 in which utility is a nested Cobb-Douglas aggregation of saving and final goods consumption. The Cobb-Douglas specification means that the shares of saving and expenditure on goods in total expenditure are kept constant. Next, the final consumption is a CES aggregation of non-energy composite and energy composite with elasticity of substitution 0.5. The non-energy composite is a Cobb-Douglas aggregate of non-energy goods, and energy composite is a Cobb-Douglas aggregate of final energy (refined oil, gas, and coal) and electricity.

The representative agent makes decisions so as to maximize his utility under the budget constraint. His income is derived from (i) factor income (capital, labor, and fossil fuel resources), (ii) various taxes revenues (output taxes, intermediate inputs taxes, consumption taxes, and trade taxes), and (iii) exogenous capital flow.

2.4 Other Components of the Model.

In the remainder of the paper, we investigate the relationship between economic growth and CO_2 emissions. Since our model is static one, all sources of economic growth are given as exogenous shocks to the economy: (i) the exogenous growth in labor force and capital stock, and (ii) technology improvements. Technology improvements are calibrated in a way described in the next section. As to policy instruments for regulating carbon emissions, we consider regulations by emission permits for estimating the relationship between income per capita and emission regulations, and afterward we employ carbon taxes as the regulation instrument.

[3] In numerical analysis, we assume that both values are twenty.

3 Dataset and Calibration.

In this section, we explain the dataset, calibration of parameters, and the way to derive the relationship between per capita income and emission regulations.[4]

3.1 Dataset.

For our analysis, we use a global economic-energy dataset GTAP-EG created by Rutherford and Paltsev (2000b). GTAP-EG is the dataset in which the global economic dataset GTAP version 4 (see Hertel, ed, 1997) and the IEA (International Energy Agency) energy datasets are combined (see Rutherford and Paltsev, 2000a, for details).[5] We aggregate the GTAP-EG dataset to sectors and regions in this paper, using the aggregation routine program provided by Rutherford and Paltsev (2000b).

Since we consider economies and emissions in the future, we need to project future economies. We use the reference case in DOE (2001) to calculate growth rates of GDP and population. To derive the labor force growth rate, we use the projection of labor force in Wold Bank (1999). Finally, we use GTAP version 4 and version 5 to derive the growth rate of capital stock. The annual growth rates employed in the simulation are given by Table 3.1.

We calibrate the technology improvements so that GDP in each region in 2010 is equal to the projected GDP calculated from DOE (2001). It is assumed that technology improvements are primary factor and energy augmented, and that improvement rates are uniform in all sectors in a region.

3.2 The Derivation of the Relationship between Emission Regulations and Income Per Capita.

The key of our analysis is the way to endogenize CO_2 regulations. We can immediately think of at least two approaches for this. (i) To assume, like the standard theoretical models, that policy makers act so as to maximize their objectives (e.g. social welfare) and decide emission regulations (e.g. Copeland and Taylor, 1994, 1995). (ii) To derive the empirical relationship which determines CO_2 emission regulations from data in the past. As to (i), it is very difficult to embed such optimization behaviors of policy makers into a large CGE model. Moreover, if you are to incorporate such behavior, you need another information about policy making, or social valuation on the environmental quality and so on. With respect to (ii), as has been already pointed out, since regulations on CO_2 emissions have not been implemented, you cannot derive the relationship which

[4]All datasets used for the simulation except GTAP version 4 datasets are available from the author upon request. Or you can download them at the author's web site, <http://park.zero.ad.jp/˜zbc08106/>. For numerical computation, we use GAMS/MPSGE (<http://www.gams.com/>) and GAMS program files are also available upon request or at the author's web site.

[5]The GTAP (Global Trade Analysis Project) dataset is widely used in numerical analyses, mainly, for trade policy. See the GTAP web site: <http://www.gtap.org/>

Table 1: The annual growth rates (%)

	GDP	Labor Force	Capital Stock	Population
USA	3.6	0.8	2.9	0.8
CAN	3.1	0.5	2.8	0.9
JPN	1.3	−0.2	2.4	0.1
WEU	2.4	0.0	1.8	0.1
OOE	3.0	0.7	2.8	0.9
EFS	3.1	0.3	1.9	0.0
CHN	7.7	0.9	8.7	0.8
IND	5.9	1.9	5.1	1.4
ASI	4.7	2.1	5.2	1.7
MPC	4.3	2.5	1.3	1.8
CSA	3.9	2.1	2.7	1.5
ROW	4.0	2.3	1.8	2.3

determines the CO_2 regulations from past dataset. Therefore, we do not adopt these approaches and employ the following one: we assume *a priori* a linear relationship between emission regulations and per capita income, and estimate parameters in the relationship from the consequences of the Kyoto Protocol type regulation which is likely to be adopted in the near future. The detailed procedure is summarized as follows:

1. Derive the equilibrium at 2010.
2. Impose the Kyoto Protocol type emission regulations.[6] We assume that there is no inter-regional permit trading among Annex I regions.
3. Then we derive per capita incomes and permit prices in all regions.
4. Let pcarb(r) denote permit price in region r, and incpc(r) denote income per capita in region r calculated in 3. Then we assume that there is the following relationship between per capita income and permit price.

$$\text{pcarb}(r) = a + b \times \text{incpc}(r) \tag{2}$$

   and estimate a and b by OLS using the values derived in 3.
5. Next, replace regulations by emission permits with regulations by carbon taxes

$$\text{carbon tax}(r) = \hat{a} + \hat{b} \times \text{incpc}(r) + \text{residual}(r) \tag{3}$$

   where carbon tax(r) is the carbon tax in region r and residual(r) is a residual corresponding to region r. We incorporate this equation into the model as a equilibrium

[6] Characteristics of the regulation are shown in Table 4.

conduction so that each region changes his carbon tax according to this and we examine the results of further economic growth.

There are two notices for this approch. First, since in this model carbon tax is equivalent to regulation by permit, replacement of two policy instruments is possible. Second, we consider regulations by emission permits only for estimating a and b, and in the analysis afterward, we employ carbon taxes as the regulation instrument.

We need to present some interpretations of the equation (3) (or (2)). Since the estimate of b turns out to be positive later, we give the interpretation assuming the positive value of b. The first interpretation is straightforward. We can view Eq. (3) as representing that countries with higher per capita income impose higher carbon taxes. In other word, richer countries impose more stringent regulations than poorer countries. Second, since carbon tax in each region is equal to the marginal abatement cost in each region, and since the marginal abatement cost is an index that represents the burden borne by him, we can interpret Eq. (3) as that richer country is willing to bear heavy burden than poorer country. In terms of these interpretations, the magnitude of b is regarded as the responsiveness of regulations to income level, or as the willingness to accept the burden. Of course, our linear specification of (3) is ad hoc in the sense that it is not based on sound theoretical foundation. However, we think that it is a good starting point for endogenizing emission regulations.

4 The Results from Simulations.

In this section, we present the major results from numerical analyses. The numerical analysis is conducted according to the following procedure:

1. Derive the equilibrium at 2010 without any emission regulation, using 1995 benchmark data, exogenous primary factor growth rates, and calibrated technology improvements.
2. Derive the equilibrium at 2010 with the Kyoto Protocol type regulation.
3. Derive the relationship between per capita income and emission regulations based on the results in 2.
4. Embed the estimated income-regulation relationship into the model and explore the results of further growth until 2020.

All cases we will consider are listed in Table 2.

4.1 The Economies at 2010 without Regulations.

Table 3 presents carbon emissions in C1995 and C2010NR , and the growth rate of carbon emissions in each region. As the values in the table show, carbon emissions significantly increase with economic growth. For example, the world total carbon emissions increase from 6.2 BtC at 1995 to 8.6 BtC at 2010 (about 38 % increase). Especially, they increase at high growth rates in rapidly growing economies such as China, India, and other Asian

Table 2: Cases.

Notations	
C1995	1995 equilibrium.
C2010NR	2010 equilibrium with no emission regulations.
C2010RE	2010 equilibrium with emission regulations.
C2020EN	2020 equilibrium with endogenous carbon taxes.
C2020CO	2020 equilibrium with constant carbon taxes. Carbon taxes are kept constant at 2010 level.

Table 3: Carbon emissions in C1995 and C2010NR, and the rate of change in emissions.

	Emissions C1995	Emissions C2010NR	Rate of change (%)
USA	1.49	1.96	31.7
CAN	0.14	0.17	23.8
WEU	0.98	1.12	14.4
JPN	0.34	0.38	11.0
OOE	0.09	0.10	19.8
EFS	0.90	1.05	15.8
CHN	0.85	1.64	93.4
IND	0.21	0.36	70.2
ASI	0.38	0.64	68.1
MPC	0.36	0.51	42.5
CSA	0.22	0.31	44.2
ROW	0.25	0.34	36.0
Annex	3.94	4.79	21.4
Non-Annex	2.27	3.81	67.9
World	6.21	8.59	38.4

Carbon emissions are measured in BtC.

countries. The growth rates of emissions in these regions are respectively given by 93.4%, 70.2%, and 68.1%. As a result of this, Non-Annex I regions as a whole exhibit the higher growth in carbon emissions than Annex I regions as a whole.

4.2 The Economies at 2010 with Regulations.

Table 4 describes the characteristics of emission regulations imposed on the economies at 2010. The numbers in the second column indicate the reduction rates of carbon emissions under the Kyoto Protocol[7]. Each Annex I region must reduce his carbon emissions at this rate below the 1990 level in 2010. The numbers in the third column indicate the associated limit on carbon emissions. Since non-Annex I regions are not imposed reduction targets, the cells associated with them are empty. The numbers in the fourth column are the effective rates of reduction at 2010. The reduction rates in the second column are represented in terms of 1990 emission levels, however, since most Annex I regions (except EFS) experience increase in emissions since 1990, the effective rates of reduction are higher than the ones in the first column.

The last column shows that carbon emissions in each region when regulations are imposed. Except EFS, emission constraints on all Annex I regions are binding, and emissions reduce to the target levels. Note that emissions from non-Annex I regions increase when we impose emission limits on Annex I regions (compare the value in Table 4 with the one in Table 3). In other words, *the carbon leakage* occurs as a result of the regulations (the leakage rate is about 12.3%). However, the world as a whole generates less emissions because of the drastic emission reduction in Annex I regions (from 8.59 BtC in C2010NR to 7.6 BtC in C2010RE).

To see the effects of regulations on economies in detail, let us make a comparison between the carbon intensities in different cases. Table 5 presents the carbon intensities in three cases: C1995, C2010NR, and C2010RE. Each value indicates the amount of carbon (kg) emitted to generate one dollar of GDP (1995 US. dollar). The table shows that from C1995 to C2010NR, carbon intensities significantly decrease in all regions. It is mainly because all regions enjoy technology improvements during this period and less energy inputs are needed to generate a unit of GDP.

Next, let us compare the values in C2010NR and C2010RE. In all regions of Annex I except EFS, carbon intensities decrease when regulations are imposed. The rates of decrease range from 33% in USA to 17% in OOE. These significant changes in carbon intensities in Annex I regions are of course due to the stringent emission regulations on them. In other words, we can say that the regulations imposed here have given large

[7] We call the regulation employed here as the Kyoto Protocol (KP) type regulation. However, there are several differences between two. First, emission reductions refered in KP means not only literal reduction in the amount of carbon emissions but also increase in carbon sink. Moreover, KP considers various GHGs other than CO_2. On the other hand, we consider only carbon emissions from fossil fuel combustion. This means that the regulation we presume is likely to overstate KP. Second, while KP allows permit trading among Annex regions (although it may be restricted), we assume that permit trading is not possible. Third, it is not clear whether KP is ratified by all Annex I countries, especially by US., we assume that all Annex I countries comply with KP.

Table 4: Limits on emissions.

	Reduction rate (%)	Emission limit	Effective rate (%)	Emissions C2010RE
USA	7	1.25	36.2	1.25
CAN	5	0.12	29.8	0.12
WEU	6	0.86	23.8	0.86
JPN	8	0.25	33.5	0.25
OOE	5	0.08	19.6	0.08
EFS	0	1.34	−27.8	1.10
CHN				1.70
IND				0.36
ASI				0.66
MPC				0.54
CSA				0.32
ROW				0.36
Annex				3.66
Non-Annex				3.94
World				7.60

Carbon emissions are measured in BtC.

shocks to the economies in Annex I regions. On the other hand, carbon intensities in non-Annex I regions slightly increase because of the factors which bring about carbon leakages.

Table 5: Carbon intensity, kg per 1995 US dollar.

	C1995	C2010NR	C2010RE
USA	0.23	0.17	0.12
CAN	0.28	0.22	0.16
WEU	0.13	0.10	0.08
JPN	0.07	0.07	0.05
OOE	0.24	0.18	0.15
EFS	1.29	0.94	0.98
CHN	1.57	1.05	1.08
IND	0.77	0.55	0.56
ASI	0.28	0.23	0.24
MPC	0.47	0.36	0.37
CSA	0.18	0.15	0.15
ROW	0.40	0.30	0.32

Table 6 and Figure 1 present the combinations of per capita income and permit price in all regions when emission regulations are imposed on Annex I regions. We can derive the relationship between per capita income and regulations of (3) using the values in Table 6. In all non-Annex I regions, and in EFS in which emission restriction is not biding, permit prices are of course zero. As numbers in the table show, per capita incomes of all Annex I regions which are imposed emission regulations tend to be higher than non-Annex I regions. In other words, a region with higher per capita income tend to impose the more stringent regulation.

Table 6: Per capita income and permit prices.

	Per capita income[a]	Permit price[b]
USA	41.0	310.7
CAN	25.5	252.2
WEU	31.8	285.7
JPN	47.9	635.3
OOE	21.8	119.8
EFS	3.0	0
CHN	1.5	0
IND	0.7	0
ASI	2.8	0
MPC	4.6	0
CSA	5.2	0
ROW	1.4	0

[a] Thousand dollar.
[b] A dollar per tons of carbon.

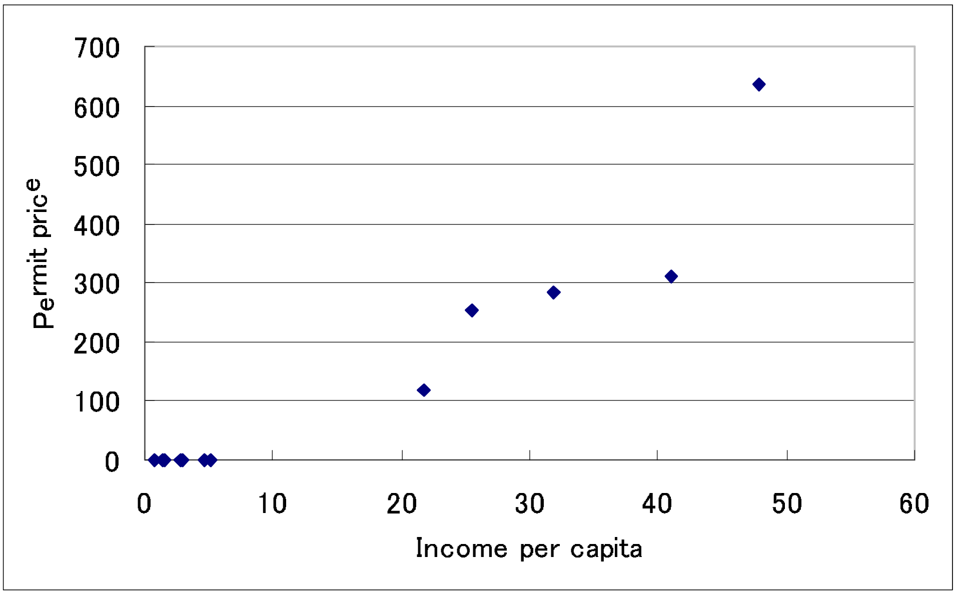

Figure 1: Income per capita and permit prices.

In Table 7, estimated $\hat{a}$ and $\hat{b}$ are presented. The sign of $\hat{b}$ is positive as we assumed before. Its size represents the responsiveness of regulations to income level or the willingness to accept the burden. The value of 1.112 of $\hat{b}$ means that one thousand of dollar increase in in per capita income leads to 1.112 dollar increase in carbon tax. In the remainder of the paper, we incorporate the equation (3) into the model so that governments in each region set the carbon tax according to (3) and examine the effects of further economic growth untill 2020.

4.3 The Economies at 2020 with Endogenous Regulations.

To derive the equilibrium at 2020, we change the exogenous variables in the model (e.g., labor force, capital stock, and technology parameters etc.) at the rate presented in Table 3.1. Table 8 shows that the states of economies at 2020 with endogenous carbon taxes. In all regions, per capita income increases with economic growth from 2010 to 2020.

Table 7: Estimates of $\hat{a}$ and $\hat{b}$.

	$\hat{a}$	$\hat{b}$
Estimates	−3.969	1.112

Especially, less developed regions display relatively high growth. In the less developed regions, the growth rate of GDP is much higher than that of per capita income because the growth rate of population is also high in these regions. With the increases in per capita income, all regions have come to impose the higher carbon taxes according to the equation (3).

Our main question is whether economic growth will increase carbon emissions or not. As the table shows, the answer is yes: in spite of the rise in carbon taxes, total carbon emissions increase significantly: from 7.60 BtC in C2010RE to 9.27 BtC in 2020EN. It is mainly because although increase in emissions from Annex I regions is modest (from 3.66 BtC to 3.96 BtC), emissions from non-Annex I regions increase dramatically (from 3.94 BtC to 5.31 BtC). This means that *the responsiveness of regulations to income change or the willingness to accept the burden ($\hat{b}$) is too weak to restrain emissions*. This is confirmed by looking at Table 9. The table presents carbon emissions and their rates of change when carbon taxes are kept constant at 2010 level (C2020CO). The difference in carbon emissions in C2020EN and C2020CO indicates the amount of carbon emissions reduced by the rise in carbon tax. Table 9 shows that the amount of carbon emissions in C2020EN is less than that in C2020CO only by a few percents. This indicates that the rise in carbon tax induced by increase in per capita income is very small and therefore the amount of carbon emissions reduced is also small.

In other words, we can conclude that, given the policy responsiveness or willingness to accept the burden estimated from the consequence of imposition of the Kyoto Protocol type regulations, the world carbon emissions are likely to increase with further economic growth.

5 Sensitivity analysis.

In this section, we conduct three sensitivity analyses and see whether the results obtained in the previous section alter or not. We consider the following parameters: (i) the estimated parameter $\hat{b}$, (ii) supply elasticity of fossil fuel, and (iii) trade elasticity.

Our specification of (3) may be a good starting point for endogenizing emission regulations, and the parameters in (3) are estimated by imposing the Kyoto Protocol type regulations which are likely to be adopted in the near future. However the specification is still a bit ad hoc. Therefore it is helpful to do sensitivity analysis of robustness of the specification. Since we found that the responsiveness of regulations $\hat{b}$ is too *weak* to reduce emissions, we try to raise the value of $\hat{b}$ and check whether the result that emissions increase with economic growth is modified or not. For this, we consider two cases: (i)

Table 8: Equilibrim at 2020 (C2020EN).

	Per capita income[a]	Carbon tax[b]	Emissions C2020EN[c]	Rate of change
USA	48.7	396.3	1.41	13.0
CAN	29.5	296.7	0.14	13.1
WEU	37.3	347.0	0.91	6.2
JPN	53.7	699.3	0.27	8.1
OOE	25.5	160.8	0.09	9.8
EFS	3.6	7.3	1.14	3.8
CHN	2.5	11.6	2.42	42.3
IND	1.0	3.3	0.50	38.4
ASI	3.7	9.9	0.92	38.1
MPC	5.3	8.6	0.65	19.9
CSA	6.3	12.2	0.40	23.9
ROW	1.5	1.6	0.43	20.0
Annex			3.96	8.2
Non-Annex			5.31	34.6
World			9.27	21.9

[a] Thousand dollar.
[b] Dollar per tons of carbon.
[c] BtC.

Table 9: Constant emission tax (C2020CO).

	Emissions C2020CO (BtC)	Rate of change (%)
USA	1.46	16.4
CAN	0.14	13.2
WEU	0.92	7.5
JPN	0.28	8.7
OOE	0.09	10.2
EFS	1.16	5.4
CHN	2.49	46.5
IND	0.51	39.2
ASI	0.93	40.0
MPC	0.66	21.6
CSA	0.40	25.7
ROW	0.43	20.1
Annex	4.03	10.3
Non-Annex	5.41	37.2
World	9.45	24.3

doubling $\hat{b}$ and (ii) tripling $\hat{b}$. The results are shown in Table 10 in which carbon taxes and carbon emissions in each case are presented.

Table 10: Sensitivity of the value of estimated $\hat{b}$.

	$2 \times \hat{b}$		$3 \times \hat{b}$	
	Carbon Tax	Emissions	Carbon Tax	Emissions
USA	479.2	1.33	559.3	1.26
CAN	339.6	0.13	381.1	0.13
WEU	407.3	0.88	466.4	0.86
JPN	762.5	0.27	824.7	0.26
OOE	199.7	0.09	236.6	0.09
EFS	14.5	1.12	21.7	1.11
CHN	23.2	2.35	34.9	2.29
IND	6.7	0.50	10.0	0.50
ASI	19.9	0.90	29.8	0.89
MPC	16.8	0.64	24.8	0.63
CSA	24.3	0.39	36.3	0.39
ROW	3.1	0.43	4.7	0.43
Annex		3.82		3.71
Non-Annex		5.21		5.13
World		9.03		8.84

Carbon tax is dollar per tons of carbon.
Emssions is BtC.

As the table shows, the carbon taxes rise to the significantly higher level in these two cases than in the base case. Nevertheless, carbon emissions increase as compared to emissions before growth (7.6 BtC).

Next, we conduct a sensitivity analysis of supply elasticity of fossil fuels (η). The high value of η means the large response of supply against price change. Since economic growth increases demand for fossil fuels and raises demand price of fossil fuels, if η is high, economic growth is likely to increase supply of fossil fuels in a large amount and thus lead to large increase in carbon emissions. We consider two cases where the value of η is doubled and halved, and see carbon emissions in each case.

Table 11 presents carbon emissions (BtC) in each case. The table shows that according to the value of η, the amount of carbon emissions differ significantly and that as pointed out above, in the higher η is, the more carbon emissions are all cases. However, even in the case of $\eta \times 1/2$ in which the rise in carbon emissions is the smallest, the result that carbon emissions increase as a result of economic growth remains unchanged.

Finally, we see the sensitivity of trade elasticities (Armington elasticity and import

Table 11: Sensitivity of supply elasticity. Emissions (BtC).

		1995	2010GR	2010RE	2020EN
$\eta \times 2$	Annex	3.94	4.98	3.69	4.04
	Non-Annex	2.27	4.00	4.08	5.68
	World	6.21	8.98	7.78	9.72
$\eta \times 1$	Annex	3.94	4.79	3.66	3.96
	Non-Annex	2.27	3.81	3.94	5.31
	World	6.21	8.59	7.60	9.27
$\eta \times 0.5$	Annex	3.94	4.51	3.61	3.84
	Non-Annex	2.27	3.56	3.77	4.85
	World	6.21	8.07	7.38	8.69

elasticity). The high value of trade elasticities means that shocks to a region will have large ripple effects on other regions through trade in goods. In our model, it means that economic growth or rise in carbon tax in a region will have large effects on other regions. We consider two cases other than the base case: doubling and halving trade elasticities. The results are shown in Table 12.

Table 12: Sensitivity of supply elasticity. Emissions (BtC).

		1995	2010GR	2010RE	2020EN
$\sigma \times 2$	Annex	3.94	4.76	3.66	3.95
	Non-Annex	2.27	3.82	3.97	5.37
	World	6.21	8.58	7.63	9.32
$\sigma \times 1$	Annex	3.94	4.79	3.66	3.96
	Non-Annex	2.27	3.81	3.94	5.31
	World	6.21	8.59	7.60	9.27
$\sigma \times 0.5$	Annex	3.94	4.79	3.66	3.97
	Non-Annex	2.27	3.75	3.88	5.17
	World	6.21	8.54	7.53	9.13

The table shows that the change in trade elasticities have relatively small effects on carbon emissions compared to the change in supply elasticity. It also shows that as trade elasticities are higher, emissions in Annex regions increase, those in non-Annex regions decrease, and world carbon emissions increase.

The opposite movements of emissions in Annex and Non-Annex regions are explained as follows:

First, the higher value of trade elasticities mean the larger leakage effect. Second, Annex regions impose more stringent regulations than non-Annex regions. Combining these two, as trade elasticities are higher, the leakage effect becomes stronger and more and more emission generating activities move to non-Annex region from Annex regions. As these results indicate, the changes in trade elasticities alter the results from simulations slightly. However, economic growth increase the amount of carbon emissions in all cases.

The sensitivity analyses above shows that various numerical results can vary according to the values of parameters. In all cases, however, the result in the previous section that economic growth leads to increase in carbon emissions remains unchanged.

6 Concluding Remarks.

In this paper, we have explored the impacts of economic growth on carbon emissions.

Our approaches are summarized as follows. First, we employ a multi-sector, multi-region global CGE model. Second, we consider explicitly the dependence of emission regulations on income level, i.e. the observation that richer countries tend to impose more stringent regulations than poorer countries. Our finding is summarized as follows. Economic growth leads to substantial increase in carbon taxes because all regions, especially less developed regions, enjoy rise in per capita income. Nevertheless, carbon emissions increase significantly as a result of economic growth. It is because the responsiveness of carbon tax against rise in income, which is estimated from Kyoto Protocol type regulations, is too weak to restrain the increase in carbon emissions. Therefore, our conclusion is that carbon emissions are likely to increase all over the world along with further economic growth. Although the Environmental Kuznets curve argument suggests that economic growth does not necessarily harm environment, our result shows that the argument is likely not to be applicable to CO_2 emissions.

References

Antweiler, W., B. R. Copeland, and M. S. Taylor (2001). “Is Free Trade Good for the Environment?” *American Economic Review.* September **91** (4), 877–908.

Armington, P. S. (1969). “A Theory of Demand for Products Distinguished by Place of Production.” IMF Staff Papers 16.

Babiker, M. H. and T. F. Rutherford (2001). “The Economic Effects of Border Measures in Subglobal Climate Aggreements.” September. presented at CREST Workshop on the Kyoto Mechanism.

Bernstein, P. M., W. D. Montgomery, and T. F. Rutherford (1999). “Global Impacts of the Kyoto Agreement: Results from the MS-MRT Model.” *Resource and Energy Economics.* **21**, 375–413.

Böhringer, C. (2000). “Cooling Down Hot Air: A Global CGE Analysis of Post-Kyoto Carbon Abatement Strategies.” *Energy Policy.* **28**, 779–789.

——— and T. F. Rutherford (2001). “Carbon Abatement and International Spillovers: A Decomposition of General Equilibrium Effects.” mimeo, (available at: `http://debreu.colorado.edu/`).

Copeland, B. R. and M. S. Taylor (1994). “North-South Trade and the Environment.” *Quarterly Journal of Economics.* August **109** (3), 755–787.

——— and ——— (1995). “Trade and Transboundary Pollution.” *American Economic Review.* September **85**, 716–27.

DOE (2001). *International Energy Outlook 2001*, Washinton, DC.: Energy Information Administration, US Department of Energy, DOE/IEA-0484(2001). (available at `http://www.eia.doe.gov/oiaf/ieo/`).

Gale, L. R. and J. A. Mendez (1998). “The Empirical Relationship between Trade, Growth and the Environment.” *International Review of Economics and Finance.* **7** (1), 53–61.

Grossman, G. M. and A. B. Krueger (1993). “Environmental Impacts of a North American Free Trade Agreement.” in P. Garber, ed., *The Mexico-U.S. Free Trade Agreement*, Cambridge, MA: MIT Press, pp. 13–56.

——— and ——— (1995). “Economic Growth and the Environment.” *Quarterly Journal of Economics.* May **110** (2), 353–377.

Hertel, T. W., ed. (1997). *Global Trade Analysis: Modeling and Applications*, New York: Cambridge University Press.

Holtz-Eakin, D. and T. M. Selden (1995). “Stoking the Fires? CO_2 emissions and Economic Growth.” *Journal of Public Economics.* **57**, 85–101.

IPCC (2000). “Emissions Scenarios: Summary for Policy Makers.” Intergovernmental Panel on Climate Change Special Report, (available at: `http://www.ipcc.ch/`).

——— (2001a). “Climate Change 2001: Impacts, Adaptation, and Vulnerability, Summary for Policy Makers.” IPCC (Intergovernmental Panel on Climate Change) Third Assessment Report, (available at: `http://www.ipcc.ch/`).

——— (2001b). “Climate Change 2001: The Scientific Basis, Summary for Policy Makers.” IPCC (Intergovernmental Panel on Climate Change) Third Assessment Report, (available at: `http://www.ipcc.ch/`).

Jorgenson, D. W. and P. J. Wilcoxen (1993). "Reducing US Carbon Emissions: An Econometric General Equilibrium Assesment." *Resource and Energy Economics.* **15**, 7–25.

McKibbin, W. J., M. T. Ross, R. Shackleton, and P. J. Wilcoxen (1999). "Emissions Trading, Capital Flows and the Kyoto Protocol." *Energy Journal.* pp. 287–333. Kyoto Special Issues.

Paltsev, S. V. (2000a). "The Kyoto Agreement: Regional and Sectoral Contributions to the Carbon Leakage." Working Paper, University of Colorad, Department of Economics, (available at: `http://ucsu.colorado.edu/˜paltsev/current.html`).

——— (2000b). "The Kyoto Protocol: "Hot Air" for Russia?" Working Paper, University of Colorad, Department of Economics,
(available at: `http://ucsu.colorado.edu/˜paltsev/current.html`).

Rutherford, T. F. (1998). "CES Preferences and Technology: A Practical Introduction." in "Economic Equilibrium Modeling with GAMS: An Introduction to GAMS/MCP and GAMS/MPSGE (GAMS/MPSGE Solver Manual)", pp. 89-115,
(available at: `http://www.gams.com/docs/solver/mpsge.pdf`).

——— and S. V. Paltsev (2000a). "GTAPinGAMS and GTAP-EG: Global Datasets for Economic Research and Illustrative Models." September. Working Paper, University of Colorad, Department of Economics,
(available at: `http://debreu.colorado.edu/gtap/gtapgams.html`).

——— and ——— (2000b). "The GTAPinGAMS package (version 2)." September.
(available at: `http://debreu.colorado.edu/gtap/gtapgams.html`).

Selden, T. M. and D. Song (1994). "Environmental Quanlity and Development: Is There a Kuznets Curve for Air Pollution Emissions?" *Journal of Environmental Economics and Management.* **27**, 147–162.

UNFCCC (1997). "Kyoto Protocol to the United Nations Framework Convention on Climate Change." (available at: `http://www.unfccc.int/`).

Wold Bank (1999). *World Development Indicators*, World Bank, Washington, D.C.

A Sector and Region Listing.

Table 13: The list of regions in the model. There are twelve regions (six Annex I regions and six non-Annex I regions). Asterisks are attached to Annex I regions.

Region identifier	Region
USA	United States *
CAN	Canada *
WEU	Western Europe *
JPN	Japan *
OOE	Other OECD (Australia and New Zealand) *
EFS	Eastern Europe and Former Soviet Union *
CHN	China
IND	India
ASI	Other Asia
MPC	Mexico and Middle East
CSA	Central and Southern America
ROW	Rest of the world

Table 14: The list of sectors in the model. There are five energy sectors and three non-energy sectors.

Sector identifier	Sector
Y	Other manufactures and services
EIS	Energy-intensive sectors
COL	Coal
OIL	Petroleum and coal products (refined)
CRU	Crude oil
GAS	Natural gas
ELE	Electricity
CGD	Saving goods

B The Production and Demand Structures of the Model.

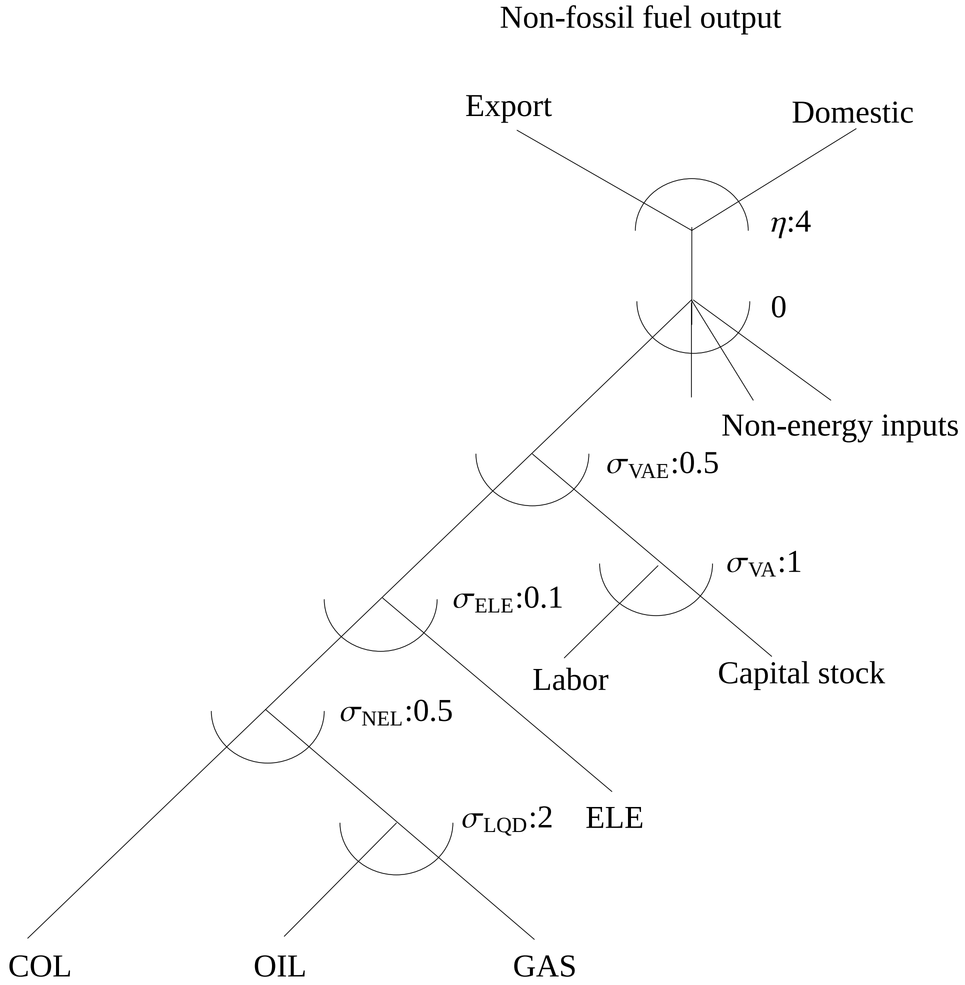

Figure 2: The nesting structure of non-fossil fuel sector.

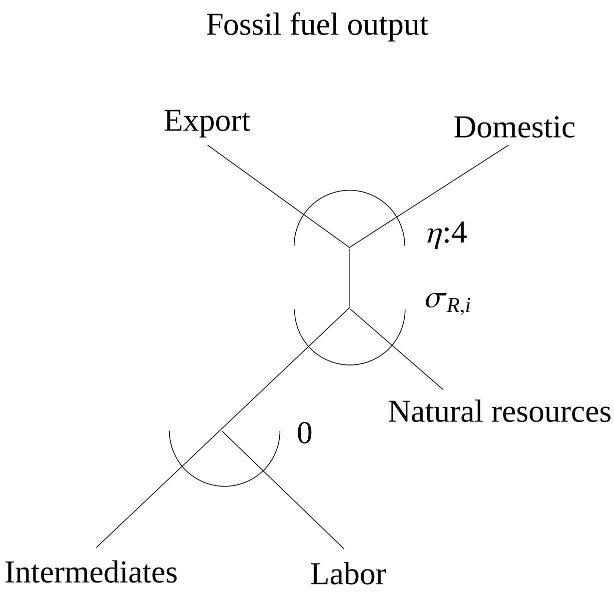

Figure 3: Fossil fuel sector.

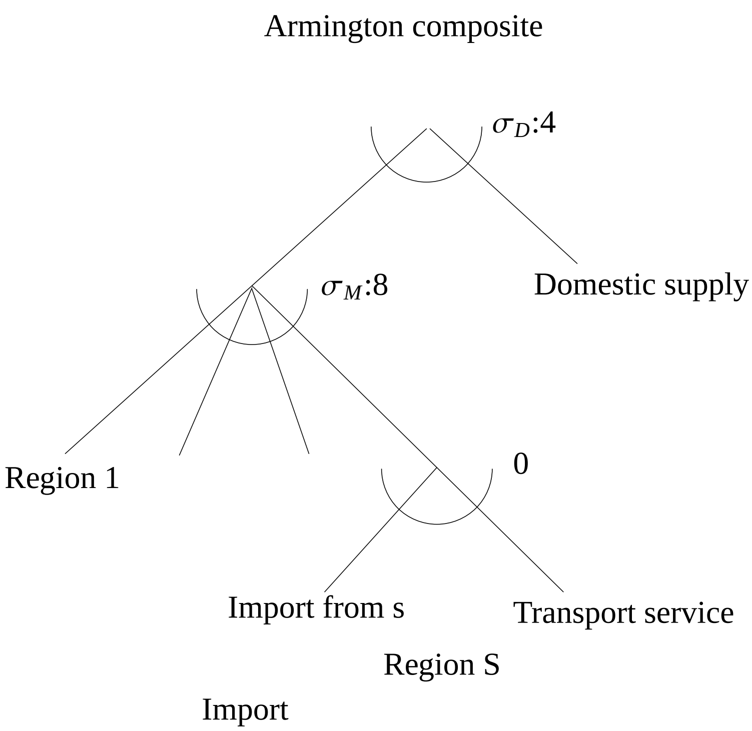

Figure 4: Armington and import aggregation sector.

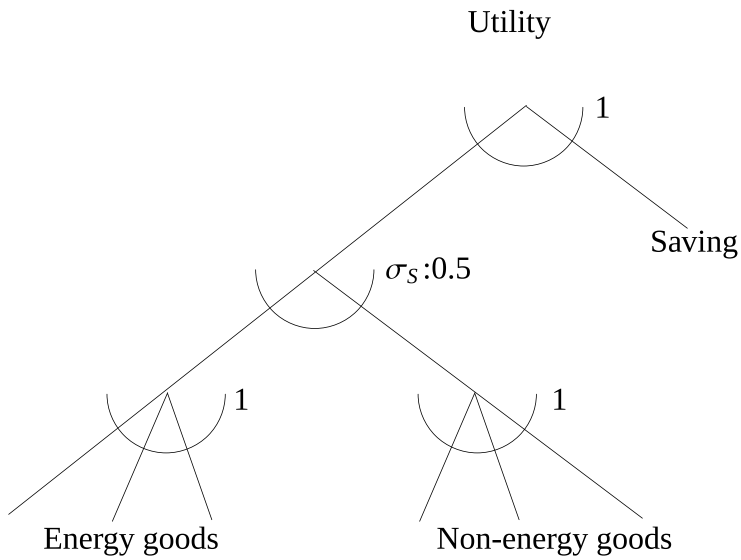

Figure 5: Utility function

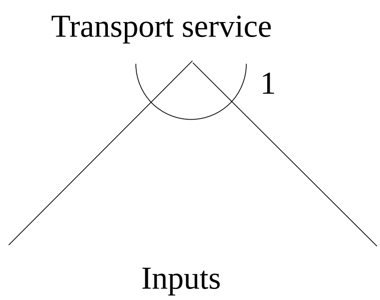

Figure 6: The production function of transport sector.

C The Algebraic Representation of the Model.

In this appendix, we present the algebraic representation of the model structure. You can find the similar representation in Böhringer (2000) and Böhringer and Rutherford (2001).

NB:

- All function are written in calibrated share form (Rutherford, 1998).
- Slack variable associated to each equation is given in the parenthesis on the right end.
- Policy instruments such as tax are omitted.

C.1 Notations

Set definitions

- r or $s \cdots$ the index of regions.
- i or $j \cdots$ the index of sectors.
- xe = CRU, COL, GAS.
- fe = COL, GAS, OIL.
- eg = COL, GAS, OIL, ELE.
- lqd = GAS, OIL.

Share parameters

- $\theta^{X}_{ir} \cdots$ Share of exports in sector i of region r.
- $\theta^{R}_{ir} \cdots$ Share of natural resources in sector i of region r ($i \in$ xe).
- $\theta^{\mathrm{xe}}_{Tir} \cdots$ Share of intermediate j ($T = j$) or labor ($T = L$) in sector i ($i \in$ xe).
- $\theta^{\mathrm{NEG}}_{jir} \cdots$ Share of non energy intermediate j ($j \notin$ eg) in sector i ($i \notin$ xe).
- $\theta^{\mathrm{VAE}}_{ir} \cdots$ Share of value added - energy aggregate in sector i ($i \notin$ xe).
- $\theta^{E}_{ir} \cdots$ Share of energy aggregate in sector i ($i \notin$ xe).
- $\theta^{L}_{ir} \cdots$ Share of labor in value added of sector i ($i \notin$ xe).
- $\theta^{\mathrm{ELE}}_{ir} \cdots$ Share of electricity in energy demand by sector i ($i \notin$ xe).
- $\theta^{\mathrm{COL}}_{ir} \cdots$ Share of coal in fossil fuel demand by sector i ($i \notin$ xe).
- $\theta^{\mathrm{LQD}}_{fe,ir} \cdots$ Share of gas or oil in liquidity fossil fuel (fe = oil or gas) demand by sector i and region r ($i \notin$ xe).
- $\theta^{\mathrm{MA}}_{ir} \cdots$ Share of aggregated imported goods in Armington good i.
- $\theta^{M}_{isr} \cdots$ Share of import of good i from region s to region r.
- $\gamma_{isr} \cdots$ Share of ...
- $\theta^{S}_{r} \cdots$ Share of saving in region r.
- $\theta^{\mathrm{CE}}_{r} \cdots$ Share of composite energy in household consumption.
- $\theta^{\mathrm{CEG}}_{ir} \cdots$ Share of energy i in household energy consumption ($i \in$ fe).
- $\theta^{\mathrm{CNE}}_{ir} \cdots$ Share of non-energy good i in household non-energy consumption ($i \notin$ fe).
- $\theta^{T}_{ir} \cdots$ Share of good i from region r in transport sector inputs.

Elasticity parameters

- $\sigma_{R,i}$ $\cdots$ Substitution between fossil fuel resources and other inputs in fossil fuel production calibrated consistently to exogenous supply elasticity ($i \in$ xe).
- σ_{VAE} $\cdots$ Substitution between energy and value added in non fossil fuel production ($i \notin$ xe).
- σ_E $\cdots$ Substitution between electricity and non-electric energy in non fossil fuel production ($i \notin$ xe).
- σ_{NEL} $\cdots$ Substitution between coal and liquidity energy in non fossil fuel production ($i \notin$ xe).
- σ_{LQD} $\cdots$ Substitution between oil and gas in non fossil fuel production ($i \notin$ xe).
- σ_D $\cdots$ Substitution between domestic goods and imported goods in Armington aggregation.
- σ_M $\cdots$ Substitution between imports from different regions.
- σ_S $\cdots$ Substitution between energy and non energy good in household consumption of region r.
- η $\cdots$ Elasticity of transformation between domestic supply and export supply in region r.

Price variables

- p_{ir} $\cdots$ Price of good i of region r supplied to the domestic market.
- p_{ir}^X $\cdots$ Price of good i of region r supplied to the export.
- p_{ir}^E $\cdots$ Price of aggregate energy in sector i ($i \notin$ xe)..
- p_{ir}^{NEL} $\cdots$ Price of non-electric energy composite demanded by sector i ($i \notin$ xe).
- p_{ir}^M $\cdots$ Price of a composite import of i.
- p_{isr}^{MM} $\cdots$ Price of import of i from region s to region r.
- p_{ir}^A $\cdots$ Price of a Armington composite of i.
- p_r^U $\cdots$ Price of utility in region r.
- p_r^{CE} $\cdots$ Price of an energy composite in final consumption.
- p_r^{CNE} $\cdots$ Price of non-energy composite in final consumption.
- pl_r $\cdots$ Wage rate in region r.
- rk_r $\cdots$ Rental rate in region r.
- p_{ir}^R $\cdots$ Price for fossil fuel resources in sector i of region r.
- p^T $\cdots$ Price of transport service.

Activity variables

- Y_{ir} $\cdots$ Production in sector i of region r.
- E_{ir}^E $\cdots$ Energy aggregation for sector i of region r ($i \notin$ xe).
- M_{ir} $\cdots$ Import aggregation of good i in region r.
- A_{ir} $\cdots$ Armington aggregation of good i in region r.
- U_r $\cdots$ Utitlity of a representative agent in region r.
- Y^T $\cdots$ Production of transport service sector.

Endowments and other variables.

- $L_r \cdots$ Endowment of labor in region r.
- $K_r \cdots$ Endowment of capital in region r.
- $R_{ir} \cdots$ Endowment of fossil fuel resources in sector i of region r ($i \notin$ xe).
- $B_r \cdots$ Balance of payment surplus in region r.
- $\mathrm{RA}_r \cdots$ Income of a representative consumer in region r.
- $\tau_{isr} \cdots$ The amount of transport service required to ship one unit of good i from region s to region r.

C.2 Zero profit conditions

Fossil fuel production sector. $i \in$ xe.

$$-\Pi_{ir}^{Y} = \left(\theta_{ir}^{R} p_{ir}^{R\,1-\sigma_{R,i}} + (1-\theta_{ir}^{R}) \left(\theta_{Lir}^{\mathrm{xe}} pl_r + \sum_j \theta_{jir}^{\mathrm{xe}} p_{jr}^{A} \right)^{1-\sigma_{R,i}} \right)^{\frac{1}{1-\sigma_{R,i}}} - \left(\theta_{ir}^{X} p_{ir}^{X\,1+\eta} + (1-\theta_{ir}^{X}) p_{ir}^{1+\eta} \right)^{\frac{1}{1+\eta}} \geq 0 \qquad \{Y_{ir}\} \tag{4}$$

Non-fossil fuel production sectors. $i \notin$ xe.

$$-\Pi_{ir}^{Y} = \sum_{j \notin \mathrm{eg}} \theta_{jir}^{\mathrm{NEG}} p_{jr}^{A} + \theta_{ir}^{\mathrm{VAE}} \left(\theta_{ir}^{E} p_{ir}^{E\,1-\sigma_{\mathrm{VAE}}} + (1-\theta_{ir}^{E}) (pl_r^{\theta_{ir}^{L}} rk_r^{1-\theta_{ir}^{L}})^{1-\sigma_{\mathrm{VAE}}} \right)^{\frac{1}{1-\sigma_{\mathrm{VAE}}}} - \left(\theta_{ir}^{X} p_{ir}^{X\,1+\eta} + (1-\theta_{ir}^{X}) p_{ir}^{1+\eta} \right)^{\frac{1}{1+\eta}} \geq 0 \qquad \{Y_{ir}\} \tag{5}$$

Sector specific energy aggragate. $i \notin$ xe.

$$-\Pi_{ir}^{E} = \left(\theta_{ir}^{\mathrm{ELE}} p_{\mathrm{ELE},r}^{A\,1-\sigma_E} + (1-\theta_{ir}^{\mathrm{ELE}}) p_{ir}^{\mathrm{NEL}\,1-\sigma_E} \right)^{\frac{1}{1-\sigma_E}} - p_{ir}^{E} \geq 0 \qquad \{E_{ir}^{E}\} \tag{6}$$

where

$$p_{ir}^{\mathrm{NEL}} = \left(\theta_{ir}^{\mathrm{COL}} p_{\mathrm{COL},r}^{A\,1-\sigma_{\mathrm{NEL}}} + (1-\theta_{ir}^{\mathrm{COL}}) \left(\sum_{j \in \mathrm{LQD}} \theta_{ir}^{j} p_{jr}^{A\,1-\sigma_{\mathrm{LQD}}} \right)^{\frac{1-\sigma_{\mathrm{NEL}}}{1-\sigma_{\mathrm{LQD}}}} \right)^{\frac{1}{1-\sigma_{\mathrm{NEL}}}} \tag{7}$$

Armington aggregation sector.

$$-\Pi_{ir}^{A} = \left(\theta_{ir}^{\mathrm{MA}} p_{ir}^{M\,1-\sigma_D} + (1-\theta_{ir}^{\mathrm{MA}}) p_{ir}^{1-\sigma_D} \right)^{\frac{1}{1-\sigma_D}} - p_{ir}^{A} \geq 0 \qquad \{A_{ir}\} \tag{8}$$

Import aggregation sector.

$$-\Pi_{ir}^{M} = \left(\sum_s \theta_{isr}^{M} p_{isr}^{\mathrm{MM}\,1-\sigma_M} \right)^{\frac{1}{1-\sigma_M}} - p_{ir}^{M} \geq 0 \qquad \{M_{ir}\} \tag{9}$$

where

$$p^{\text{MM}}_{irs} = \gamma_{irs} p^X_{ir} + (1 - \gamma_{irs}) p^T \tau_{irs} \tag{10}$$

Utitlity production sector.

$$-\Pi^U_r = p^{A\,\theta^S_r}_{\text{cgd}} \left(\theta^{\text{CE}}_r p^{\text{CE}\,1-\sigma_S}_r + (1 - \theta^{\text{CE}}_r) p^{\text{CNE}\,1-\sigma_S}_r \right)^{\frac{1-\theta^S_r}{1-\sigma_S}} - p^U_r \geq 0 \qquad \{U_r\} \tag{11}$$

where

$$p^{\text{CNE}}_r = \prod_{i \notin \text{eg}} p^{A\,\theta^{\text{CNE}}_{ir}}_{ir} \qquad p^{\text{CE}}_r = \prod_{i \in \text{eg}} p^{A\,\theta^{\text{CEG}}_{ir}}_{ir} \tag{12}$$

Transport sector.

$$-\Pi^T = \prod_{i,r} p^{X\,\theta^T_{ir}}_{ir} - p^T \geq 0 \qquad \{Y^T\} \tag{13}$$

C.3 Market clearing conditions.

Markets for capital and labor.

$$L_r \geq \sum_i Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial pl_r} \qquad \{pl_r\} \tag{14}$$

$$K_r \geq \sum_i Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial rk_r} \qquad \{rk_r\} \tag{15}$$

Market for natural resources. $i \in \text{xe}$.

$$R_{ir} \geq Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^R_{ir}} \qquad \{p^R_{ir}\} \tag{16}$$

Market for domestic supply.

$$Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p_{ir}} \geq A_{ir} \frac{\partial \Pi^A_{ir}}{\partial p_{ir}} \qquad \{p_{ir}\} \tag{17}$$

Market for export supply

$$Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^X_{ir}} \geq \sum_s M_{is} \frac{\partial \Pi^M_{is}}{\partial p^X_{ir}} + Y^T \frac{\partial \Pi^T}{\partial p^X_{ir}} \qquad \{p^X_{ir}\} \tag{18}$$

Market for sector specific energy aggregate. $i \notin \text{xe}$.

$$E_{ir} \geq Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^E_{ir}} \qquad \{p^E_{ir}\} \tag{19}$$

Market for aggregated imports.

$$M_{ir} \geq A_{ir} \frac{\partial \Pi_{ir}^{A}}{\partial p_{ir}^{M}} \qquad \{p_{ir}^{M}\} \tag{20}$$

Market for Armington aggregate.

$$A_{ir} \geq \sum_{j} Y_{jr} \frac{\partial \Pi_{jr}^{Y}}{\partial p_{ir}^{A}} + U_r \frac{\partial \Pi_{r}^{U}}{\partial p_{ir}^{A}} \qquad \{p_{ir}^{A}\} \tag{21}$$

Market for utility.

$$U_r \geq \mathrm{RA}_r / p_r^{U} \qquad \{p_r^{U}\} \tag{22}$$

C.4 Income

$$\begin{aligned}
\mathrm{RA}_r \leq\ & rk_r K_r && \text{Capital income} \\
& + pl_r L_r && \text{Labor income} \\
& + \sum_{i \in xe} p_{ir}^{R} R_{ir} && \text{Revenue from fossil fuel resources} \\
& + B_r && \text{Capital inflow} \\
& + \text{Tax revenue}
\end{aligned}$$